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(54) **HIGH TENSILE STRENGTH GALVANIZED STEEL SHEETS EXCELLENT IN FORMABILITY AND METHODS OF MANUFACTURING THE SAME**

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(57) **ABSTRACT**

A formable galvanized steel sheet includes, in terms of % by mass, 0.05 to 0.3% of C, 0.01 to 2.5% of Si, 0.5 to 3.5% of Mn, 0.003 to 0.100% of P, 0.02% or less of S, 0.010 to 1.5% of Al, and 0.01 to 0.2% in total of at least one element selected from Ti, Nb and V, the remainder being Fe and unavoidable impurities, having a microstructure composed of, in terms of area fraction, 20 to 87% of ferrite, 3 to 10% in total of martensite and residual austenite, and 10 to 60% of tempered martensite, and a second phase composed of the martensite, residual austenite, and tempered martensite having an average crystal grain diameter of 3 μm or less, and having a ratio of absorption energy AE to tensile strength TS (AE/TS) not less than 0.063.

7 Claims, No Drawings

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**HIGH TENSILE STRENGTH GALVANIZED
STEEL SHEETS EXCELLENT IN
FORMABILITY AND METHODS OF
MANUFACTURING THE SAME**

TECHNICAL FIELD

This disclosure relates to high tensile strength galvanized steel sheets and methods of making the same, the galvanized steel sheets being excellent in formability and anti-crush properties and used in industrial fields such as automobile and electrical industries.

BACKGROUND

In recent years, from the standpoint of global environment protection, improvement of fuel efficiency of automobiles is an important issue. Therefore, there is a growing tendency to reduce car body weight by increasing the tensile strength and reducing the thickness of the steel sheet composing a car. The increase of the tensile strength of the car body material contributes to the improvement of crush safety, so that high tensile strength steel sheets are increasingly used as car body materials. However, in general cases, the increase of the tensile strength of a steel sheet can result in the deterioration of the ductility of the steel sheet, or the deterioration of formability. Therefore, there is a demand for a galvanized steel sheet having high tensile strength and high formability, and excellent corrosion resistance.

High tensile strength galvanized steel sheets of the multiphase type such as DP (Dual Phase) steel composed of ferrite and martensite, and TRIP (Transformation Induced Plasticity) steel utilizing transformation induced plasticity of residual austenite have been developed to satisfy such a demand.

“Tetsu To Hagane (Iron and Steel),” Vol. 83 (1997), p. 748 describes that ferrite-martensite two-phase steel exhibits excellent anti-crush properties. However, the ferrite-martensite two-phase steel has an r value of less than 1.0, and low deep drawability, so that its applicability is limited.

Japanese Unexamined Patent Application Publication No. 11-279691 proposes a high tensile strength galvanized steel sheet with good formability, the steel sheet containing, in terms of % by mass, 0.05 to 0.15% of C, 0.3 to 1.5% of Si, 1.5 to 2.8% of Mn, 0.03% or less of P, 0.02% or less of S, 0.005 to 0.5% of Al, 0.0060% or less of N, the remainder being Fe and unavoidable impurities, the elemental composition satisfying $(\text{Mn} \%)/(\text{C} \%)\geq 15$ and $(\text{Si} \%)/(\text{C} \%)\geq 4$, and the steel sheet being composed of ferrite containing, in terms of volume fraction, 3 to 20% of martensite and residual austenite. However, these high tensile strength galvanized steel sheets of the composite structure type exhibit high elongation E1 as determined by uniaxial stretching, but have poor stretch-flangeability required for a hole expansion process and the like.

Therefore, Japanese Unexamined Patent Application Publication No. 6-93340 discloses a method for making a high tensile strength galvanized steel sheet with excellent stretch-flangeability. Under the method, a steel sheet composed of, in terms of % by mass, 0.02 to 0.30% of C, 1.5% or less of Si, 0.60 to 3.0% of Mn, 0.20% or less of P, 0.05% or less of S, 0.01 to 0.10% of Al, the remainder being Fe and unavoidable impurities, is subjected to hot rolling at a temperature not lower than the Ac_3 transformation point, pickled and cold-rolled, and the steel sheet is heated and maintained at a temperature not lower than the recrystallization temperature and Ac_1 transformation point on a continuous annealing

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galvanizing line. Subsequently, before immersion in a galvanizing bath, the steel sheet is rapidly cooled to the Ms point or lower thereby forming martensite partially or wholly in the steel sheet, and then heated to a temperature not lower than the Ms point and at least equal to the galvanizing bath temperature and galvannealing furnace temperature thereby forming partially or completely tempered martensite.

The high tensile strength galvanized steel sheet described in JP '340 provides excellent stretch-flangeability. However, the product of tensile strength TS and E1 as determined by uniaxial stretching, or the TS-E1 balance of the steel sheet is low. The ratio of yield strength YS to TS, or yield ratio YR (YS/TS) is high, which results in poor formability. In addition, the steel sheet has poor anti-crush properties which are necessary for securing crush safety.

It could therefore be helpful to provide a high tensile strength galvanized steel sheet with excellent formability and a method for making the same, the steel sheet providing a high TS-E1 balance, excellent stretch-flangeability, and a low YR. It could also be helpful to provide a high tensile strength galvanized steel sheet with excellent anti-crush properties and a method for making the same, the steel sheet providing a high TS-E1 balance and excellent stretch-flangeability.

SUMMARY

We provide a formable galvanized steel sheet, including in terms of % by mass, 0.05 to 0.3% of C, 0.01 to 2.5% of Si, 0.5 to 3.5% of Mn, 0.003 to 0.100% of P, 0.02% or less of S, 0.010 to 1.5% of Al, and 0.01 to 0.2% in total of at least one element selected from Ti, Nb and V, the remainder being Fe and unavoidable impurities, having a microstructure composed of, in terms of area fraction, 20 to 87% of ferrite, 3 to 10% in total of martensite and residual austenite, and 10 to 60% of tempered martensite, and a second phase composed of the martensite, residual austenite, and tempered martensite having an average crystal grain diameter of 3 μm or less, and having a ratio of absorption energy AE to tensile strength TS (AE/TS) not less than 0.063.

We also provide the formable galvanized steel sheet, including in terms of % by mass, 0.05 to 0.3% of C, 0.01 to 2.5% of Si, 0.5 to 3.5% of Mn, 0.003 to 0.100% of P, 0.02% or less of S, 0.010 to 1.5% of Al, and 0.01 to 0.2% in total of at least one element selected from Ti, Nb and V, the remainder being Fe and unavoidable impurities, having a microstructure composed of, in terms of area fraction, 20 to 87% of ferrite, 3 to 10% in total of martensite and residual austenite, and 10 to 60% of tempered martensite, and a second phase composed of the martensite, residual austenite, and tempered martensite having an average crystal grain diameter of 3 μm or less, and having a ratio of absorption energy AE to tensile strength TS (AE/TS) not less than 0.063, further including at least one composition selected from the group consisting of (A) to (C): (A): at least one element selected from the group consisting of, in terms of % by mass, 0.005 to 2.00% of Cr, 0.005 to 2.00% of Mo, 0.005 to 2.00% of Ni, and 0.005 to 2.00% of Cu; (B): in terms of % by mass, 0.0002 to 0.005% of B; and (C): at least one element selected from the group consisting of, in terms of % by mass, 0.001 to 0.005% of Ca and 0.001 to 0.005% of REM.

We further provide the formable galvanized steel sheet, including in terms of % by mass, 0.05 to 0.3% of C, 0.01 to 2.5% of Si, 0.5 to 3.5% of Mn, 0.003 to 0.100% of P, 0.02% or less of S, 0.010 to 1.5% of Al, and 0.01 to 0.2% in total

of at least one element selected from Ti, Nb and V, the remainder being Fe and unavoidable impurities, having a microstructure composed of, in terms of area fraction, 20 to 87% of ferrite, 3 to 10% in total of martensite and residual austenite, and 10 to 60% of tempered martensite, and a second phase composed of the martensite, residual austenite, and tempered martensite having an average crystal grain diameter of 3 μm or less, and having a ratio of absorption energy AE to tensile strength TS (AE/TS) not less than 0.063, wherein the galvanized steel sheet is a galvanized steel sheet.

We further yet provide the formable galvanized steel sheet, including in terms of % by mass, 0.05 to 0.3% of C, 0.01 to 2.5% of Si, 0.5 to 3.5% of Mn, 0.003 to 0.100% of P, 0.02% or less of S, 0.010 to 1.5% of Al, and 0.01 to 0.2% in total of at least one element selected from Ti, Nb and V, the remainder being Fe and unavoidable impurities, having a microstructure composed of, in terms of area fraction, 20 to 87% of ferrite, 3 to 10% in total of martensite and residual austenite, and 10 to 60% of tempered martensite, and a second phase composed of the martensite, residual austenite, and tempered martensite having an average crystal grain diameter of 3 μm or less, and having a ratio of absorption energy AE to tensile strength TS (AE/TS) not less than 0.063, further including at least one composition selected from the group consisting of (A) to (C): (A): at least one element selected from the group consisting of in terms of % by mass, 0.005 to 2.00% of Cr, 0.005 to 2.00% of Mo, 0.005 to 2.00% of Ni, and 0.005 to 2.00% of Cu; (B): in terms of % by mass, 0.0002 to 0.005% of B; and (C): at least one element selected from the group consisting of, in terms of % by mass, 0.001 to 0.005% of Ca and 0.001 to 0.005% of REM, wherein the galvanized steel sheet is a galvanized steel sheet.

We still further provide a method of producing a formable galvanized steel sheet including: subjecting a slab having then elemental composition to hot rolling and cold rolling thereby making a cold rolled steel sheet; subjecting the cold rolled steel sheet to annealing including heating the steel sheet in a temperature range from 500° C. to the Ac_1 transformation point at an average temperature rising rate of 10° C./s or more; heating and maintaining the steel sheet in a temperature range from the Ac_1 transformation point to (Ac_3 transformation point+30° C.) for 10 seconds or more; cooling the steel sheet to a temperature range from (Ms point-100° C.) to (Ms point-200° C.) at an average cooling rate of 10° C./s or more; reheating and maintaining the steel sheet in a temperature range from 350 to 600° C. for 1 to 600 seconds; and subjecting the annealed steel sheet to galvanizing treatment.

We also further provide the method of producing a formable galvanized steel sheet including: subjecting a slab having then elemental composition to hot rolling and cold rolling thereby making a cold rolled steel sheet; subjecting the cold rolled steel sheet to annealing including heating the steel sheet in a temperature range from 500° C. to the Ac_1 transformation point at an average temperature rising rate of 10° C./s or more; heating and maintaining the steel sheet in a temperature range from the Ac_1 transformation point to (Ac_3 transformation point+30° C.) for 10 seconds or more; cooling the steel sheet to a temperature range from (Ms point-100° C.) to (Ms point-200° C.) at an average cooling rate of 10° C./s or more; reheating and maintaining the steel sheet in a temperature range from 350 to 600° C. for 1 to 600 seconds; and subjecting the annealed steel sheet to galva-

nizing treatment, wherein the average temperature rising rate from 500° C. to the Ac_1 transformation point is 20° C./s or more.

We also further provide the method of producing a formable galvanized steel sheet including: subjecting a slab having then elemental composition to hot rolling and cold rolling thereby making a cold rolled steel sheet; subjecting the cold rolled steel sheet to annealing including heating the steel sheet in a temperature range from 500° C. to the Ac_1 transformation point at an average temperature rising rate of 10° C./s or more; heating and maintaining the steel sheet in a temperature range from the Ac_1 transformation point to (Ac_3 transformation point+30° C.) for 10 seconds or more; cooling the steel sheet to a temperature range from (Ms point-100° C.) to (Ms point-200° C.) at an average cooling rate of 10° C./s or more; reheating and maintaining the steel sheet in a temperature range from 350 to 600° C. for 1 to 600 seconds; and subjecting the annealed steel sheet to galvanizing treatment, wherein the galvanizing treatment is followed by galvannealing treatment.

We produce a high tensile strength providing a high TS-E1 balance, excellent stretch-flangeability, and excellent anti-crush properties. Through the use of the high tensile strength galvanized steel sheet as an car body, the car has a reduced weight, improved corrosion resistance, and improved crush safety.

DETAILED DESCRIPTION

We discovered high tensile strength galvanized steel sheets with excellent formability providing a high TS-E1 balance (specifically $TS \times E1 \geq 19000$ MPa-%), excellent stretch-flangeability (specifically the below-described hole expansion ratio satisfies $\lambda \geq 70\%$), and a low YR (specifically $YR < 75\%$) that include:

- i) excellent stretch-flangeability, a high TS-E1 balance, and a low YR are achieved with a microstructure having an optimized elemental composition and containing, in terms of area fraction, 20 to 87% of ferrite, 3 to 10% in total of martensite and residual austenite, and 10 to 60% of tempered martensite; and
- ii) the microstructure is produced through annealing including forced cooling from 750 to 950° C. to a temperature range from (Ms point-100° C.) to (Ms point-200° C.), and then reheating, followed by galvanizing treatment. The Ms point is the temperature at which transformation from austenite to martensite begins, and can be determined from the variation of the coefficient of linear expansion of the steel during cooling.

We thus provide high tensile strength galvanized steel sheets with excellent formability, the steel sheet containing, in terms of % by mass, 0.05 to 0.3% of C, 0.01 to 2.5% of Si, 0.5 to 3.5% of Mn, 0.003 to 0.100% of P, 0.02% or less of S, 0.010 to 1.5% of Al, and 0.007% or less of N, the remainder being Fe and unavoidable impurities, and the steel sheet having a microstructure composed of, in terms of area fraction, 20 to 87% of ferrite, 3 to 10% in total of martensite and residual austenite, and 10 to 60% of tempered martensite.

The high tensile strength galvanized steel sheets may further contain one or more elements selected from, in terms of % by mass, 0.005 to 2.00% of Cr, 0.005 to 2.00% of Mo, 0.005 to 2.00% of V, 0.005 to 2.00% of Ni, and 0.005 to 2.00% of Cu. In addition, the steel sheet may further contain one or two elements selected from, in terms of % by mass, 0.01 to 0.20% of Ti and 0.01 to 0.20% of Nb, and one or

more elements selected from 0.0002 to 0.005% of B, 0.001 to 0.005% of Ca, and 0.001 to 0.005% of REM.

The high tensile strength galvanized steel sheets may be a galvanized or galvanized steel sheet.

The high tensile strength galvanized steel sheets may be produced by, for example, a method of making a high tensile strength galvanized steel sheet with excellent formability, including steps of subjecting a slab having the above-described elemental composition to hot rolling and cold rolling thereby making a cold rolled steel sheet, subjecting the cold rolled steel sheet to annealing including steps of heating and maintaining the steel sheet in a temperature range from 750 to 950° C. for 10 seconds or more, cooling the steel sheet from 750° C. to a temperature range from (Ms point-100° C.) to (Ms point-200° C.) at an average cooling rate of 10° C./s or more, and reheating and maintaining the steel sheet in a temperature range from 350 to 600° C. for 1 to 600 seconds, and then subjecting the annealed steel sheet to galvanizing treatment.

Under the method of making a high tensile strength galvanized steel sheet, the galvanizing treatment may be followed by galvanizing treatment.

We produce high tensile strength galvanized steel sheets with excellent formability providing a high TS-E1 balance, excellent stretch-flangeability, and a low YR. Through the use of the high tensile strength galvanized steel sheet as a car body, the car has a decreased weight, improved corrosion resistance, and improved crush safety.

We also discovered high tensile strength galvanized steel sheets providing a high TS-E1 balance (specifically TS×E1≥19000 MPa·%), excellent stretch-flange-ability (specifically the below-described hole expansion ratio, λ≥70%), and excellent anti-crush properties (specifically the below-described ratio of the absorption energy AE and TS, AE/TS≥0.063), including:

- iii) excellent stretch-flangeability, a high TS-E1 balance, and excellent anti-crush properties are achieved with a microstructure having an optimized elemental composition and containing, in terms of area fraction, 20 to 87% of ferrite, 3 to 10% in total of martensite and residual austenite, and 10 to 60% of tempered martensite, the second phase composed of the martensite, residual austenite, and tempered martensite having an average crystal grain diameter of 3 μm or less; and
- iv) the microstructure is produced through annealing including steps of heating the steel sheet in a temperature range from 500° C. to the Ac₁ transformation point at an average temperature rising rate of 10° C./s or more, heating and maintaining the steel sheet in a temperature range from the Ac₁ transformation point to (Ac₃ transformation point+30° C.) for 10 seconds or more thereby forming more fine austenite through transformation, forcedly cooling the steel sheet to a temperature range from (Ms point-100° C.) to (Ms point-200° C.) at an average cooling rate of 10° C./s or more, and reheating the steel sheet, and then subjecting the annealed steel sheet to galvanizing treatment. The Ms point is the temperature at which transformation from austenite to martensite begins, and can be determined from the variation of the coefficient of linear expansion of the steel during cooling.

We thus provide high tensile strength galvanized steel sheets with excellent formability and anti-crush properties, the steel sheets containing, in terms of % by mass, 0.05 to 0.3% of C, 0.01 to 2.5% of Si, 0.5 to 3.5% of Mn, 0.003 to 0.100% of P, 0.02% or less of S, 0.010 to 1.5% of Al, in addition, 0.01 to 0.2% in total of at least one element

selected from Ti, Nb, and V, the remainder being Fe and unavoidable impurities, the steel sheets having a microstructure composed of, in terms of area fraction, 20 to 87% of ferrite, 3 to 10% in total of martensite and residual austenite, and 10 to 60% of tempered martensite, and the second phase composed of the martensite, residual austenite, and tempered martensite having an average crystal grain diameter of 3 μm or less.

The high tensile strength galvanized steel sheets may further contain one or more elements selected from, in terms of % by mass, 0.005 to 2.00% of Cr, 0.005 to 2.00% of Mo, 0.005 to 2.00% of Ni, and 0.005 to 2.00% of Cu. In addition, as necessary, the steel sheets may further contain one or more elements selected from, in terms of % by mass, 0.0002 to 0.005% of B, 0.001 to 0.005% of Ca, and 0.001 to 0.005% of REM.

The high tensile strength galvanized steel sheets may be a galvanized or galvanized steel sheet.

The high tensile strength galvanized steel sheets may be produced by, for example, a making method including steps of subjecting a slab having the above-described elemental composition to hot rolling and cold rolling thereby making a cold rolled steel sheet, subjecting the cold rolled steel sheet to annealing including steps of heating the steel sheets in a temperature range from 500° C. to the Ac₁ transformation point at an average temperature rising rate of 10° C./s or more, heating and maintaining the steel sheets in a temperature range from the Ac₁ transformation point to (Ac₃ transformation point+30° C.) for 10 seconds or more, cooling the steel sheets to a temperature range from (Ms point-100° C.) to (Ms point-200° C.) at an average cooling rate of 10° C./s or more, and reheating and maintaining the steel sheets in a temperature range from 350 to 600° C. for 1 to 600 seconds, and then subjecting the annealed steel sheets to galvanizing treatment.

The galvanizing treatment may be followed by galvanizing treatment.

Details of the steel sheets and methods are described below. The “%” expressing the content of an element means “% by mass” unless otherwise stated.

1) Elemental Composition

C: 0.05 to 0.3%

C is an element stabilizing austenite, and necessary for forming the second phase such as martensite other than ferrite thereby increasing the TS and improving the TS-E1 balance. If the C content is less than 0.05%, formation of the second phase other than ferrite is inhibited, and thus the TS-E1 balance deteriorates. On the other hand, if the C content is more than 0.3%, the weldability deteriorates. Accordingly, the C content is from 0.05 to 0.3%, preferably from 0.08 to 0.15%.

Si: 0.01 to 2.5%

Si is an element effective at solute strengthening steel thereby improving the TS-E1 balance. The Si content must be 0.01% or more to achieve this. If the Si content is more than 2.5%, E1 deteriorates and the surface quality and weldability deteriorate. Accordingly, the Si content is from 0.01 to 2.5%, preferably from 0.7 to 2.0%.

Mn: 0.5 to 3.5%

Mn is an element effective at strengthening steel, and promoting the formation of the second phase such as martensite. The Mn content must be 0.01% or more to achieve this. On the other hand, if the Mn content is more than 3.5%, the ductility of ferrite markedly deteriorates due to the excessive increase in the size of the second phase and solute

strengthening, which results in the deterioration of formability. Accordingly, the Mn content is from 0.5 to 3.5%, preferably from 1.5 to 3.0%.

P: 0.003 to 0.100%

P is an element effective at strengthening steel. The P content must be 0.003 or more to achieve this. On the other hand, if the P content is more than 0.100%, the steel is embrittled by grain boundary segregation, which results in the deterioration of the anti-crush properties. Accordingly, the P content is from 0.003 to 0.100%.

S: 0.02% or Less

S occurs as an intervening substance such as MnS, and deteriorates the anti-crush properties and weldability. Therefore, the Si content is preferably as low as possible. However, from the viewpoint of production cost, the S content is 0.02% or less.

Al: 0.010 to 1.5%

Al is an element effective at forming ferrite thereby improving the TS-E1 balance. The Al content must be 0.010% or more to achieve this. On the other hand, if the Al content is more than 1.5%, slab cracking tends to occur during continuous casting. Accordingly, the Al content is from 0.010 to 1.5%.

N: 0.007% or Less

N is an element deteriorating the aging resistance of the steel. If the N content is more than 0.007%, the aging resistance markedly deteriorates. Accordingly, the N content is 0.007% or less, and is preferably as low as possible.

at Least One Selected from Ti, Nb, and V: 0.01 to 0.2% in Total

Ti, Nb, and V are elements which precipitate in the forms of, for example, TiC, NbC, and VC, and are effective at refining the steel structure. The total content of the at least one element selected from Ti, Nb, and V must be 0.01% or more to achieve this. On the other hand, if the total content of the at least one element selected from Ti, Nb, and V is more than 0.2%, excessive precipitation occurs, which results in the deterioration of the ductility of ferrite. Accordingly, the total content of the at least one element selected from Ti, Nb, and V is from 0.01 to 0.2%.

The remainder is composed of Fe and unavoidable impurities, and as necessary may further contain, for the below-described reason, 0.005 to 2.00% of Cr, 0.005 to 2.00% of Mo, 0.005 to 2.00% of V, 0.005 to 2.00% of Ni, 0.005 to 2.00% of Cu, 0.01 to 0.20% of Ti, 0.01 to 0.20% of Nb, 0.0002 to 0.005% of B, 0.001 to 0.005% of Ca, and 0.001 to 0.005% of REM. Cr, Mo, V, Ni, and Cu: 0.005 to 2.00% each

Cr, Mo, V, Ni, and Cu are elements effective at inhibiting the formation of perlite during cooling from the heating temperature in annealing, and promoting the formation of martensite and other phases thereby reinforcing the steel. The content of the at least one element selected from Cr, Mo, V, Ni, and Cu must be 0.005% to achieve this. On the other hand, if the respective contents of Cr, Mo, V, Ni, and Cu are more than 2.00%, the effect is saturated, which results in an increase in cost. Accordingly, the respective contents of Cr, Mo, V, Ni, and Cu are from 0.005 to 2.00%.

Ti and Nb: 0.01 to 0.20% Each

Ti and Nb are elements effective at forming carbonitrides, and increasing the tensile strength of the steel through precipitation strengthening. The content of the at least one element selected from Ti and Nb must be 0.01% or more to achieve this. On the other hand, if the respective contents of Ti and Nb are more than 0.20%, the tensile strength is

excessively increased, which results in the deterioration of ductility. Accordingly, the respective contents of Ti and Nb are from 0.01 to 0.20%.

B: 0.0002 to 0.005%

B is an element effective at inhibiting the formation of ferrite from the austenite grain boundary, and forming a second phase such as martensite to increase the tensile strength of the steel. The B content must be 0.0002% or more to achieve this. On the other hand, if the B content is more than 0.005%, the effect is saturated, which results in an increase in cost. Accordingly, the B content is from 0.0002 to 0.005%.

Ca, REM: 0.001 to 0.005% Each

Ca and REM are elements effective at improving formability through the control of the sulfide form. The content of the at least one element selected from Ca and REM must be 0.001% or more to achieve this. On the other hand, if the respective contents of Ca and REM are more than 0.005%, steel cleanliness may be affected. Accordingly, the respective contents of Ca and REM are from 0.001 to 0.005%.

2) Microstructure

Area Fraction of Ferrite: 20 to 87%

Ferrite improves the TS-E1 balance.

To satisfy $TS \times E1 \geq 19000$ MPa-%, the area fraction of ferrite must be 20% or more, preferably 50% or more. As described below, the total area fraction of martensite and residual austenite is 3% or more, and the area fraction of tempered martensite is 10% or more, so that the upper limit of the area fraction of ferrite is 87%.

Total Area Fraction of Martensite and Residual Austenite: 3 to 10%

Martensite and residual austenite contribute to reinforcement of the steel, improve the TS-E1 balance, and decrease the YR. The total area fraction of martensite and residual austenite must be 3% or more to achieve this. However, if the total area fraction of martensite and residual austenite is more than 10%, the stretch-flangeability deteriorates. Therefore, the total area fraction of martensite and residual austenite is from 3 to 10%.

Area Fraction of Tempered Martensite: 10 to 60%

Tempered martensite affects the stretch-flangeability less than martensite before tempering or residual austenite, so that an effective second phase is formed achieving high tensile strength while maintaining excellent stretch-flangeability satisfying $\lambda \geq 50\%$. The area fraction of tempered martensite must be 10% or more to achieve this. However, if the area fraction of tempered martensite is more than 60%, $TS \times E1 \geq 19000$ MPa-% is not satisfied. Accordingly, the area fraction of tempered martensite is from 10 to 60%.

Average Crystal Grain Diameter of Second Phase Composed of Martensite, Residual Austenite, and Tempered Martensite: 3 μ m or Less

The presence of the second phase composed of martensite, residual austenite, and tempered martensite effectively improves the anti-crush properties. In particular, when the average crystal grain diameter of the second phase is 3 μ m or less, $AE/TS \geq 0.063$ is satisfied. Accordingly, the average crystal grain diameter of the second phase composed of martensite, residual austenite, and tempered martensite is preferably 3 μ m or less.

In addition to martensite, residual austenite, and tempered martensite, the second phase may further contain perlite and bainite. Good results are achieved as long as the above-described area fractions of ferrite, martensite, residual austenite, and tempered martensite, and the average crystal

grain diameter of the second phase are satisfied. From the viewpoint of stretch-flangeability, the area fraction of perlite is preferably 3% or less.

The area fractions of ferrite, martensite, residual austenite, and tempered martensite refer to the proportions of the respective phases in the observed area, and were determined as follows: a section of a steel sheet in the thickness direction was polished, corroded with 3% nital, the quarter-thickness position was observed with an SEM (scanning electron microscope) under a magnification of 1000× to 3000×, and the area fraction was calculated using commercial image processing software. The total area of the second phase composed of martensite, residual austenite, and tempered martensite was divided by the total number of second phase grains to calculate the average area of one second phase grain, and its square root was used as the average crystal grain diameter of the second phase.

3) Production Conditions 1

The high tensile strength galvanized steel sheets may be produced by, for example, a method including steps of subjecting a slab having the above-described elemental composition to hot rolling and cold rolling thereby making a cold rolled steel sheet, subjecting the cold rolled steel sheet to annealing including steps of heating and maintaining the steel sheet in a temperature range from 750 to 950° C. for 10 seconds or more, cooling the steel sheet from 750° C. to a temperature range from (Ms point–100° C.) to (Ms point–200° C.) at an average cooling rate of 10° C./s or more, and reheating and maintaining the steel sheet in a temperature range from 350 to 600° C. for 1 to 600 seconds, and then subjecting the annealed steel sheet to galvanizing treatment. Heating Conditions During Annealing: Temperature Range from 750 to 950° C. For 10 Seconds or More

If the heating temperature during annealing is lower than 750° C., or the maintaining period is less than 10 seconds, austenite is insufficiently formed, so that the second phase such as martensite is insufficiently formed by subsequent cooling. On the other hand, if the heating temperature is higher than 950° C., austenite is coarsened, whereby formation of ferrite during cooling is inhibited, and the area fraction of ferrite falls short of 20%. Accordingly, heating temperature during annealing is maintained in a temperature range from 750 to 950° C. for 10 seconds or more. The upper limit of the maintaining period is not particularly defined. However, even if the heating temperature is maintained for 600 seconds or more, the effect is saturated, which results in an increase in cost. Accordingly, the maintaining period is preferably less than 600 seconds.

Cooling Conditions During Annealing: from 750° C. To a Temperature Range from (Ms Point–100° C.) to (Ms Point–200° C.) at an Average Cooling Rate of 10° C./s or More

After heating, the steel sheet must be cooled from 750° C. at an average cooling rate of 10° C./s or more. If the average cooling rate is less than 10° C./s, perlite is formed in large amounts, so that necessary amounts of tempered martensite, martensite, and residual austenite cannot be obtained. The upper limit of the cooling rate is not particularly defined, but is preferably 200° C./s or less to prevent deterioration of the shape of the steel sheet, and to avoid difficulty regarding stopping of cooling within the temperature range from (Ms point–100° C.) to (Ms point–200° C.). The temperature at which cooling is stopped is one of the most important factors for controlling the amounts of martensite, residual austenite, and tempered martensite formed by the subsequent reheating, galvanizing, and galvannealing of the coated phase. More specifically, the amounts of martensite and untransformed martensite are determined when cooling is stopped,

and the subsequent heat treatment transforms martensite into tempered martensite, and untransformed austenite into martensite or residual austenite, whereby the strength, TS-E1 balance, stretch-flangeability, and YR of the steel are determined. If the temperature at which cooling is stopped is higher than (Ms point–100° C.), martensite is insufficiently transformed, so that the amount of untransformed austenite increases, and the total area fraction of martensite and residual austenite exceeds 10%, which results in the deterioration of the stretch-flangeability. On the other hand, if the temperature at which cooling is stopped is lower than (Ms point–200° C.), most of austenite is transformed into martensite, the amount of untransformed austenite decreases, and the total area fraction of martensite and residual austenite is below 3%, which results in the deterioration of the TS-E1 balance and increase of the YR. Accordingly, the cooling treatment during annealing must be carried out from 750° C. to a temperature range from (Ms point–100° C.) to (Ms point–200° C.) at an average cooling rate of 10° C./s or more.

Reheating Conditions During Annealing: Temperature Range from 350 to 600° C. for 1 to 600 seconds

After cooling to the temperature range from (Ms point–100° C.) to (Ms point–200° C.) at an average cooling rate of 10° C./s or more, reheating is carried out, and a temperature range from 350 to 600° C. is maintained for 1 second or more to temper the martensite formed during cooling thereby forming tempered martensite at an area fraction of 10 to 60%. As a result of this, high tensile strength is achieved and excellent stretch-flangeability is maintained. If the reheating temperature is below 350° C. or the maintaining period is less than 1 second, the area fraction of the tempered martensite is less than 10%, which results in the deterioration of the stretch-flangeability. On the other hand, if the reheating temperature is higher than 600° C. or the maintaining period is more than 600 seconds, the untransformed austenite formed during cooling is transformed into perlite or bainite, and finally the total area fraction of martensite and residual austenite is less than 3%, which results in the deterioration of the TS-E1 balance or the increase of the YR. Accordingly, the reheating temperature during annealing must be maintained within a temperature range from 350 to 600° C. for 1 to 600 seconds.

Other conditions of the production method are not particularly limited, but are preferably the following conditions.

The slab is preferably produced by a continuous casting process to prevent macro segregation, and may be produced by an ingot casting or thin slab casting process. Hot rolling of the slab may be carried out by once cooling the slab to room temperature, followed by reheating, or by charging the slab into a heating furnace without cooling the slab to room temperature. Alternatively, an energy saving process may be used, wherein the slab is slightly insulated, and then subjected to hot rolling. When the slab is heated, the heating temperature is preferably 1100° C. or higher to dissolve the carbide and prevent the increase of the rolling load. Further, to prevent the increase of scale loss, the heating temperature for the slab is preferably 1300° C. or lower.

During hot rolling of the slab, from the viewpoint of securing the rolling temperature, the rough bar after rough rolling may be heated. Alternatively, a so-called “continuous rolling” process may be used, wherein two rough bars are joined together, and subjected to continuous finish rolling. To prevent the deterioration of formability after cold rolling and annealing, and the formation of a band structure which can increase the anisotropy, the finish rolling is carried out at a temperature not lower than the Ar₃ transformation point.

Further, to reduce the rolling load and improve the uniformity of the shape and material, lubrication rolling is preferably carried out in the whole or partial path of finish rolling thereby giving a coefficient of friction of 0.10 to 0.25.

From the viewpoints of temperature control and prevention of decarbonization, the steel sheet after hot rolling is preferably wound up at a temperature of 450 to 700° C.

The wound steel sheet is subjected to pickling thereby removing scales, and then cold rolling at a rolling ratio of preferably 40% or more. Subsequently, the steel sheet is annealed under the above-described conditions, and then galvanized.

The galvanizing treatment is carried out by immersing the steel sheet in a galvanizing bath at 440 to 500° C. containing 0.12 to 0.22% of Al (when no galvannealing is involved) or 0.08 to 0.18% of Al (when followed by galvannealing), and then the coating weight is adjusted by, for example, gas wiping. The galvanizing treatment may be followed by galvannealing treatment at 450 to 600° C. for 1 to 30 seconds.

The galvanized steel sheet or galvannealed steel sheet may be subjected to temper rolling for the purpose of shape correction or adjustment of surface roughness. Further, various coating treatments such as resin or oil coating may be applied.

4) Production Conditions 2

The high tensile strength galvanized steel sheet may be produced by, for example, a method including steps of subjecting a slab having the above-described elemental composition to hot rolling and cold rolling thereby making a cold rolled steel sheet, subjecting the cold rolled steel sheet to annealing including steps of heating the steel sheet to a temperature range from 500° C. to Ac_1 transformation point at an average temperature rising rate of 10° C./s or more, heating and maintaining the steel sheet in a temperature range from Ac_1 transformation point to (Ac_3 transformation point+30° C.) for 10 seconds or more, cooling the steel sheet from 750° C. to a temperature range from (Ms point-100° C.) to (Ms point-200° C.) at an average cooling rate of 10° C./s or more, and reheating and maintaining the steel sheet in a temperature range from 350 to 600° C. for 1 to 600 seconds, and then subjecting the annealed steel sheet to galvanizing treatment.

Temperature Rising Conditions During Annealing: Temperature Rising in a Temperature Range from 500° C. to Ac_1 Transformation Point at a Temperature Rising Rate of 10° C./s or More

The temperature rising rate during annealing is an important factor for refining the average crystal grain diameter of the second phase composed of martensite, residual austenite, and tempered martensite. In the steel having the elemental composition, fine carbides of Ti, Nb, and V inhibit recrystallization. When the temperature is risen in a temperature range from 500° C. to Ac_1 transformation point at an average temperature rising rate of 10° C./s or more, the steel sheet is heated to the subsequent temperature range from the Ac_1 transformation point with little recrystallization. Therefore, during heating, the uncrystallized ferrite causes austenite transformation to form fine austenite. As a result, the second phase after cooling and reheating has an average crystal grain diameter of 3 μm or less, whereby excellent anti-crush properties satisfying $AE/TS \geq 0.063$ are achieved. On the other hand, if the average temperature rising rate in the temperature range from 500° C. to Ac_1 transformation point is less than 10° C./s, recrystallization occurs during temperature rising in the temperature range from 500° C. to Ac_1 transformation point, and the recrystallized ferrite causes

austenite transformation after grain growth to a degree. As a result, austenite is not refined, and the average crystal grain diameter of the second phase cannot be 3 μm or less. Accordingly, it is necessary to rise the temperature in the temperature range from 500° C. to Ac_1 transformation point at an average temperature rising rate of 10° C./s or more, preferably 20° C./s or more.

Heating Conditions During Annealing: Temperature Range from Ac_1 Transformation Point to (Ac_3 Transformation Point+30° C.) for 10 Seconds or More

If the heating temperature during annealing is below the Ac_1 transformation point, or the maintaining period is less than 10 seconds, formation of austenite does not occur, or insufficiently occurs, so that a sufficient amount of second phase such as martensite cannot be secured by subsequent cooling. On the other hand, if the heating temperature is higher than (Ac_3 transformation point+30° C.), austenite grains markedly grow, whereby refinement of austenite is inhibited. In addition, the growth of austenite grains inhibits formation of ferrite during cooling, so that the area fraction of ferrite cannot be 20% or more. Accordingly, the heating treatment during annealing must be carried out in a temperature range from Ac_1 transformation point to (Ac_3 transformation point+30° C.) for 10 seconds or more. From the viewpoints of inhibition of austenite coarsening and energy cost, the maintaining period is preferably 300 seconds or less.

Cooling Conditions During Annealing: Cooling from the Heating Temperature to a Temperature Range from (Ms Point-100° C.) to (Ms Point-200° C.) at an Average Cooling Rate of 10° C./s or More

After the heating treatment, the steel sheet must be cooled from the heating temperature at an average cooling rate of 10° C./s or more. If the average cooling rate is below 10° C./s, perlite is heavily formed, so that necessary amounts of tempered martensite, martensite, and residual austenite cannot be obtained. The upper limit of the cooling rate is not particularly defined, but is preferably 200° C./s or less to prevent deterioration of the shape of the steel sheet, and avoid difficulty at stopping cooling within the temperature range from (Ms point-100° C.) to (Ms point-200° C.).

The temperature at which cooling is stopped is one of the most important factors for controlling the amounts of martensite, residual austenite, and tempered martensite formed by the subsequent reheating, galvanizing, and galvannealing of the coated phase. More specifically, the amounts of martensite and untransformed martensite are determined when cooling is stopped, and the subsequent heat treatment transforms martensite into tempered martensite, and untransformed austenite into martensite or residual austenite, whereby the strength, TS-E1 balance, stretch-flangeability, and YR of the steel are determined. If the cooling treatment is stopped at a temperature higher than (Ms point-100° C.), martensite is insufficiently transformed, so that the amount of untransformed austenite increases, and the total area fraction of martensite and residual austenite exceeds 10%, which results in the deterioration of the stretch-flangeability. On the other hand, if the cooling temperature is stopped at a temperature lower than (Ms point-200° C.), most of austenite is transformed into martensite, the amount of untransformed austenite decreases, and the total area fraction of martensite and residual austenite is below 3%, which results in the deterioration of the TS-E1 balance. Accordingly, the cooling treatment during annealing must be carried out from the heating temperature to a temperature range from (Ms point-100° C.) to (Ms point-200° C.) at an average cooling rate of 10° C./s or more.

Reheating Conditions During Annealing: Temperature Range from 350 to 600° C. for 1 to 600 Seconds

After cooling to the temperature range from (Ms point–100° C.) to (Ms point–200° C.) at an average cooling rate of 10° C./s or more, reheating is carried out, and a temperature range from 350 to 600° C. is maintained for 1 second or more to temper the martensite formed during cooling thereby forming tempered martensite at an area fraction of 10 to 60%. As a result, high tensile strength is achieved with excellent stretch-flangeability maintained. If the reheating temperature is below 350° C. or the maintaining period is less than 1 second, the area fraction of the tempered martensite is less than 10%, which results in the deterioration of the stretch-flangeability. On the other hand, if the reheating temperature is higher than 600° C. or the maintaining period is more than 600 seconds, the untransformed austenite formed during cooling is transformed into perlite or bainite, and finally the total area fraction of martensite and residual austenite is less than 3%, which results in the deterioration of the TS-E1 balance. Accordingly, the reheating temperature during annealing must be maintained within a temperature range from 350 to 600° C. for 1 to 600 seconds.

Other conditions of the production method are not particularly limited, but are preferably the following conditions.

The slab is preferably produced by a continuous casting process to prevent macro segregation, and may be produced by an ingot casting or thin slab casting process. Hot rolling of the slab may be carried out by once cooling the slab to room temperature, followed by reheating, or by charging the slab into a heating furnace without cooling the slab to room temperature. Alternatively, an energy saving process may be used, wherein the slab is slightly insulated, and then subjected to hot rolling. When the slab is heated, the heating temperature is preferably 1100° C. or higher to dissolve the carbide and prevent the increase of the rolling load. Further, the heating temperature for the slab is preferably 1300° C. or lower to prevent the increase of scale loss.

During hot rolling of the slab, from the viewpoint of securing the rolling temperature, the rough bar after rough rolling may be heated. Alternatively, a so-called “continuous rolling” process may be used, wherein two rough bars are joined together, and subjected to continuous finish rolling. To prevent the deterioration of formability after cold rolling and annealing, and the formation of a band structure which can increase the anisotropy, the finish rolling is carried out at a temperature not lower than the A_{r3} transformation point. Further, to reduce the rolling load and improve the uniformity of the shape and material, lubrication rolling is preferably carried out in the whole or partial path of finish rolling thereby giving a coefficient of friction of 0.10 to 0.25.

From the viewpoints of temperature control and prevention of decarbonization, the steel sheet after hot rolling is preferably wound up at a temperature of 450 to 700° C.

The wound steel sheet is subjected to pickling thereby removing scales, and then cold rolling at a rolling ratio of preferably 40% or more. Subsequently, the steel sheet is annealed under the above-described conditions, and then galvanized.

The galvanizing treatment is carried out by immersing the steel sheet in a galvanizing bath at 440 to 500° C. containing 0.12 to 0.22% of Al (when no galvannealing is involved) or 0.08 to 0.18% of Al (when followed by galvannealing), and then the coating weight is adjusted by, for example, gas wiping. The galvanizing treatment may be followed by galvannealing treatment at 450 to 600° C. for 1 to 30 seconds.

The galvanized steel sheet or galvannealed steel sheet may be subjected to temper rolling for the purpose of shape correction or adjustment of surface roughness. Further, various coating treatments such as resin or oil coating may be applied.

EXAMPLES

Example 1

The steels A to S having the elemental compositions shown in Table 1 were ingoted by a converter, made into slabs by a continuous casting process. Subsequently, the slabs were subjected to hot rolling at a finish temperature of 900° C. to give a thickness of 3.0 mm, cooled at a cooling rate of 10° C./s, and then wound up at a temperature of 600° C. Subsequently, after pickling, the slabs were subjected to cold rolling to give a thickness of 1.2 mm, and annealed on a continuous galvanizing line under the conditions shown in Tables 2 and 3. Thereafter, the steel sheets were immersed in a galvanizing bath at 460° C. to form a coating at a coating weight of 35 to 45 g/m², subjected to galvannealing treatment at 520° C., and cooled at a cooling rate of 10° C./s to make galvanized steel sheets 1 to 44. As shown in Tables 2 and 3, some galvanized steel sheets were not subjected to galvannealing treatment. The galvanized steel sheets thus obtained were measured for the area fractions of ferrite, martensite, residual austenite, and tempered martensite by the above-described method. Further, JIS No. 5 tensile test specimens were cut out along and perpendicular to the rolling direction, and subjected to tensile test according to JIS Z 2241. Further, test specimens of 150 mm×150 mm were cut out, and subjected to hole expansion test three times according to JFS T 1001 (Japan Iron and Steel Federation standard) to determine the average hole expansion ratio λ (%), whereby the stretch-flangeability was evaluated.

The results are shown in Tables 4 and 5, indicating that all of our galvanized steel sheets satisfied TSE1 \geq 19000 MPa·%, hole expansion ratio $\lambda\geq$ 70, and YR<75%, representing their high TS-E1 balance, excellent stretch-flangeability, and low YR.

TABLE 1

Steel	Elemental composition (% by mass)																REM Note	
	C	Si	Mn	P	S	Al	N	Cr	Mo	V	Ni	Cu	Ti	Nb	B	Ca		
A	0.06	1.0	2.3	0.020	0.003	0.035	0.003	—	—	—	—	—	—	—	—	—	—	Within the scope of our methods
B	0.12	1.5	2.0	0.015	0.002	0.037	0.002	—	—	—	—	—	—	—	—	—	—	Within the scope of our methods
C	0.16	0.7	1.4	0.017	0.004	0.700	0.005	—	—	—	—	—	—	—	—	—	—	Within the scope of our methods
D	0.25	0.02	1.8	0.019	0.002	0.041	0.004	—	—	—	—	—	—	—	—	—	—	Within the scope of our methods

TABLE 1-continued

Elemental composition (% by mass)																	
Steel	C	Si	Mn	P	S	Al	N	Cr	Mo	V	Ni	Cu	Ti	Nb	B	Ca	REM Note
E	0.10	1.3	2.1	0.025	0.003	0.036	0.004	—	—	—	—	—	—	—	—	—	Within the scope of our methods
F	0.20	0.3	1.6	0.013	0.005	0.028	0.005	—	—	—	—	—	—	—	—	—	Within the scope of our methods
G	0.13	1.3	1.2	0.008	0.006	0.031	0.003	0.60	—	—	—	—	—	—	—	—	Within the scope of our methods
H	0.16	0.6	2.7	0.014	0.002	0.033	0.004	—	0.3	—	—	—	—	—	—	—	Within the scope of our methods
I	0.08	1.0	2.2	0.007	0.003	0.025	0.002	—	—	0.1	—	—	—	—	—	—	Within the scope of our methods
J	0.12	1.1	1.9	0.007	0.002	0.033	0.001	—	—	—	0.5	—	—	—	—	—	Within the scope of our methods
K	0.10	1.5	2.7	0.014	0.001	0.042	0.003	—	—	—	—	0.3	—	—	—	—	Within the scope of our methods
L	0.10	0.6	1.9	0.021	0.005	0.015	0.004	—	—	—	—	—	0.05	—	—	—	Within the scope of our methods
M	0.16	1.2	2.9	0.006	0.004	0.026	0.002	—	—	—	—	—	—	0.03	—	—	Within the scope of our methods
N	0.09	2.0	2.1	0.012	0.003	0.028	0.005	—	—	—	—	—	0.02	—	0.001	—	Within the scope of our methods
O	0.08	1.0	2.2	0.010	0.002	0.046	0.001	0.30	—	—	—	—	—	—	—	0.003	Within the scope of our methods
P	0.07	1.3	2.9	0.019	0.004	0.036	0.003	—	—	—	—	—	—	0.04	—	—	0.002 Within the scope of our methods
Q	<u>0.04</u>	1.4	1.6	0.013	0.002	0.022	0.002	—	—	—	—	—	—	—	—	—	Beyond the scope of our methods
R	0.15	0.5	<u>3.6</u>	0.022	0.001	0.036	0.002	—	—	—	—	—	—	—	—	—	Beyond the scope of our methods
S	0.08	1.2	<u>0.4</u>	0.007	0.003	0.029	0.002	—	—	—	—	—	—	—	—	—	Beyond the scope of our methods

TABLE 2

Annealing conditions											
Galvanized steel sheet No.	Steel	Heating temperature (end-point temperature) (° C.)	Heating maintaining period (s)	Cooling rate (° C./s)	Cooling end-point (° C.)	Reheating temperature (° C.)	Reheating maintaining period (s)	Ms point (° C.)	Galvan-nealing	Note	
1	A	830	60	50	200	400	40	353	Treated	Example	
2		<u>720</u>	60	50	120	400	30	245	Treated	Comparative Example	
3		810	60	50	<u>100</u>	420	30	341	Treated	Comparative Example	
4	B	780	90	80	180	430	60	318	Treated	Example	
5		780	<u>5</u>	80	70	430	60	184	Treated	Comparative Example	
6		800	60	80	<u>50</u>	400	60	329	Treated	Comparative Example	
7	C	880	90	30	150	450	45	265	Untreated	Example	
8		880	90	<u>5</u>	<u>120</u>	450	45	196	Untreated	Comparative Example	
9		880	90	30	<u>30</u>	450	45	265	Untreated	Comparative Example	
10	D	780	150	70	140	450	60	261	Treated	Example	
11		780	60	150	<u>20</u>	450	60	237	Treated	Comparative Example	
12		780	90	100	<u>200</u>	450	50	250	Treated	Comparative Example	
13	E	850	75	80	170	400	30	297	Treated	Example	
14		850	60	80	160	<u>300</u>	60	279	Treated	Comparative Example	
15		830	75	80	160	<u>650</u>	60	279	Treated	Comparative Example	
16		850	75	80	40	400	30	297	Treated	Comparative Example	
17	F	800	240	90	100	400	90	248	Treated	Example	
18		820	240	90	100	400	<u>0</u>	270	Treated	Comparative Example	
19		800	240	90	100	450	<u>900</u>	282	Treated	Comparative Example	
20		800	240	90	<u>220</u>	400	90	248	Treated	Comparative Example	
21	G	850	60	100	150	500	30	279	Treated	Example	
22		850	60	100	<u>20</u>	500	30	279	Treated	Comparative Example	

TABLE 3

Galvanized steel sheet No.	Steel	Annealing conditions						Ms point (° C.)	Galvan- nealing	Note
		Heating temperature (end-point temperature) (° C.)	Heating maintaining period (s)	Cooling rate (° C./s)	Cooling end-point (° C.)	Reheating temperature (° C.)	Reheating maintaining period (s)			
23	H	840	120	90	190	400	30	316	Treated	Example
24		840	120	90	<u>50</u>	400	30	316	Treated	Comparative Example
25		<u>1000</u>	120	150	200	350	30	380	Treated	Comparative Example
26	I	830	75	150	250	500	45	380	Treated	Example
27		830	75	150	<u>300</u>	500	45	380	Treated	Comparative Example
28	J	800	45	80	180	400	20	319	Untreated	Example
29		800	45	80	<u>50</u>	400	20	319	Untreated	Comparative Example
30	K	750	200	100	210	550	10	348	Treated	Example
31		750	200	100	<u>50</u>	550	10	348	Treated	Comparative Example
32	L	780	120	150	230	400	60	342	Treated	Example
33		780	120	150	<u>300</u>	400	60	342	Treated	Comparative Example
34	M	840	90	150	180	400	20	341	Untreated	Example
35		840	90	150	<u>280</u>	400	20	341	Untreated	Comparative Example
36	N	820	60	50	160	450	90	308	Treated	Example
37		820	60	50	<u>50</u>	450	90	308	Treated	Comparative Example
38	O	800	45	1000	220	450	150	389	Treated	Example
39		800	45	1000	<u>20</u>	450	150	389	Treated	Comparative Example
40	P	860	30	30	200	450	30	377	Treated	Example
41		860	30	30	<u>320</u>	450	30	377	Treated	Comparative Example
42	<u>Q</u>	800	60	30	200	400	60	328	Treated	Comparative Example
43	<u>R</u>	820	90	80	180	400	30	347	Treated	Comparative Example
44	<u>S</u>	820	75	80	20	400	120	121	Treated	Comparative Example

TABLE 4

Galvanized steel sheet No.	Microstructure*										Note
	F				Tensile characteristic values						
	Area fraction (%)	M + residual γ Area fraction (%)	Tempered M Area fraction (%)	Other	YS (MPa)	TS (MPa)	El (%)	YR (%)	TS \times El (MPa \cdot %)	λ (%)	
1	80	4	16	—	389	670	32	58	21440	74	Example
2	<u>90</u>	<u>2</u>	<u>2</u>	P	502	605	25	83	15125	50	Comparative Example
3	82	<u>1</u>	17	—	518	682	26	76	17732	81	Comparative Example
4	72	5	18	B	553	801	27	69	21627	85	Example
5	85	4	<u>5</u>	P	628	730	22	86	16060	45	Comparative Example
6	70	<u>1</u>	29	—	632	810	23	78	18630	84	Comparative Example
7	77	7	14	P	715	979	21	73	20559	74	Example
8	82	<u>2</u>	<u>8</u>	P	767	913	17	84	15521	56	Comparative Example
9	77	<u>1</u>	22	—	792	990	18	80	17820	77	Comparative Example
10	59	9	32	—	788	1065	18	74	19170	71	Example
11	63	<u>1</u>	36	—	874	1040	15	84	15600	90	Comparative Example
12	61	<u>23</u>	12	B	783	1103	14	71	15442	40	Comparative Example
13	79	6	15	—	481	697	30	69	20910	75	Example
14	81	<u>13</u>	<u>6</u>	—	508	782	27	65	21114	46	Comparative Example
15	81	<u>1</u>	13	P	584	704	21	83	14784	72	Comparative Example
16	77	<u>1</u>	22	—	544	706	25	77	17650	80	Comparative Example
17	70	6	24	—	618	858	23	72	19734	78	Example
18	67	<u>14</u>	19	—	593	885	22	67	19470	56	Comparative Example
19	65	<u>1</u>	34	—	697	820	20	85	16400	85	Comparative Example
20	72	<u>17</u>	<u>6</u>	B	546	910	21	60	19110	27	Comparative Example
21	78	5	17	—	418	686	32	61	21952	78	Example
22	75	<u>1</u>	24	—	537	698	25	77	17450	79	Comparative Example

*F ferrite, M martensite, γ austenite, P pearlite, B bainite

TABLE 5

Galvanized steel sheet No.	Microstructure*					Tensile characteristic values						λ (%)	Note
	F		Tempered M			YS (MPa)	TS (MPa)	El (%)	YR (%)	TS × El (MPa · %)			
	Area (%)	M + residual γ Area fraction (%)	Area ratio (%)	Other									
23	55	10	35	—	812	1113	18	73	20034	72	Example		
24	56	2	42	—	926	1129	15	82	16935	80	Comparative Example		
25	5	8	87	—	1085	1220	9	89	10980	85	Comparative Example		
26	64	9	27	—	629	861	24	73	20664	78	Example		
27	64	23	11	B	563	923	22	61	20306	27	Comparative Example		
28	71	6	23	—	594	825	25	72	20625	75	Example		
29	74	2	24	—	676	834	21	81	17514	76	Comparative Example		
30	62	8	30	—	671	958	23	70	22034	79	Example		
31	60	1	39	—	804	980	19	82	18620	85	Comparative Example		
32	73	8	19	—	589	830	23	71	19090	74	Example		
33	74	14	7	B	566	885	22	64	19470	43	Comparative Example		
34	40	7	53	—	935	1299	16	72	20784	82	Example		
35	40	31	29	—	863	1370	15	63	20550	38	Comparative Example		
36	80	4	16	—	587	839	26	70	21814	83	Example		
37	77	1	22	—	715	851	22	84	18722	78	Comparative Example		
38	60	6	34	B	583	845	24	69	20280	81	Example		
39	60	0	40	—	680	861	20	79	17220	85	Comparative Example		
40	58	6	36	—	801	1112	19	72	21128	83	Example		
41	60	22	18	—	761	1171	18	65	21078	25	Comparative Example		
42	91	1	8	—	363	471	35	77	16485	62	Comparative Example		
43	15	9	76	—	1028	1224	12	84	14688	75	Comparative Example		
44	93	1	4	P	245	335	45	73	15075	65	Comparative Example		

*F ferrite, M martensite, γ austenite, P pearlite, B bainite

Example 2

The steels AA to AL having the elemental compositions shown in Table 6 were ingoted by a converter, made into slabs by a continuous casting process. Subsequently, the slabs were subjected to hot rolling at a finish temperature of 900° C. to give a thickness of 3.0 mm, cooled at a cooling rate of 10° C./s, and then wound up at a temperature of 600° C. Subsequently, after pickling, the slabs were subjected to cold rolling to give a thickness of 1.2 mm, and annealed on a continuous galvanizing line under the conditions shown in Tables 7. Thereafter, the steel sheets were immersed in a galvanizing bath at 460° C. to form a coating layer at a coating weight of 35 to 45 g/m², subjected to galvannealing treatment at 520° C., and cooled at a cooling rate of 10° C./s to make galvanized steel sheets 101 to 130. As shown in Table 7, some galvanized steel sheets were not subjected to galvannealing treatment. The galvanized steel sheets thus obtained were measured for the area fractions of ferrite, martensite, residual austenite, and tempered martensite, and the average crystal grain diameter of the second phase composed of martensite, residual austenite, and tempered

30 martensite by the above-described methods. Further, JIS No. 5 tensile test specimens were cut out along and perpendicular to the rolling direction, and subjected to tensile test according to JIS Z 2241 to determine TS×E1. Further, test specimens of 150 mm×150 mm were cut out, and subjected to hole expansion test three times according to JFS T 1001 (Japan Iron and Steel Federation standard) to determine the average hole expansion ratio λ(%), whereby the stretch-flangeability was evaluated. Further, according to the method described in “Tetsu To Hagane (Iron and Steel),” Vol. 83 (1997), p. 748, test specimens having a width of 5 mm and a length of 7 mm were cut out along and perpendicular to the rolling direction, and subjected to tensile test at a strain rate of 2000/s. The stress-true strain curve was integrated over the strain amount of 0 to 10% to calculate the absorption energy AE and AE/TS, whereby the anti-crush properties were evaluated.

The results are shown in Tables 8 and 9, indicating that all of our galvanized steel sheets satisfied TSE1≥19000 MPa·%, hole expansion ratio λ≥50, and AE/TS≥0.063, representing their high TS-E1 balance, excellent stretch-flangeability, and excellent anti-crush properties.

TABLE 6

Steel	Elemental composition (% by mass)																Ac ₁ Transformation point (° C.)	Ac ₃ Transformation point (° C.)	Note
	C	Si	Mn	P	S	Al	Ti	Nb	V	Cr	Mo	Ni	Cu	B	Ca	REM			
AA	0.10	1.0	2.0	0.011	0.005	0.03	0.04	—	—	—	—	—	—	—	—	—	721	875	Within the scope of our methods
AB	0.08	0.8	2.5	0.010	0.002	0.04	—	0.02	—	—	—	—	—	—	—	—	710	851	Within the scope of our methods

TABLE 6-continued

Steel	Elemental composition (% by mass)																Ac ₁	Ac ₃	Note
	C	Si	Mn	P	S	Al	Ti	Nb	V	Cr	Mo	Ni	Cu	B	Ca	REM	(° C.)	(° C.)	
AC	0.21	1.4	1.6	0.009	0.010	0.03	—	—	0.05	0.2	—	—	—	—	—	—	735	876	Within the scope of our methods
AD	0.14	2.0	1.8	0.008	0.004	0.60	0.10	—	—	—	0.3	—	—	—	—	—	684	896	Within the scope of our methods
AE	0.18	0.2	2.2	0.012	0.003	0.04	0.02	0.03	—	—	—	0.3	—	0.001	—	—	706	805	Within the scope of our methods
AF	0.09	1.2	1.4	0.009	0.001	0.30	—	0.02	0.02	—	—	—	0.2	—	0.003	—	742	920	Within the scope of our methods
AG	0.12	1.5	1.9	0.007	0.007	0.05	0.05	—	0.03	0.3	—	—	—	—	0.005	—	737	892	Within the scope of our methods
AH	0.08	0.9	2.3	0.012	0.004	0.03	0.10	0.03	—	0.03	0.1	—	—	0.002	—	—	718	863	Within the scope of our methods
AI	0.11	1.8	2.0	0.021	0.005	1.20	0.01	0.01	—	—	—	—	—	—	0.002	0.001	734	886	Within the scope of our methods
AJ	<u>0.03</u>	0.5	1.4	0.008	0.006	0.04	0.02	—	—	—	—	—	—	—	—	—	719	883	Within the scope of our methods
AK	0.07	0.2	<u>0.2</u>	0.009	0.004	0.05	—	0.03	—	—	—	—	—	—	—	—	728	899	Within the scope of our methods
AL	0.12	1.0	1.8	0.011	0.003	0.03	—	—	—	—	—	—	—	—	—	—	723	876	Within the scope of our methods

TABLE 7

Annealing conditions												Note
Galvanized steel sheet No.	Steel	Heating rate (° C./s)	Heating temperature (end-point temperature) (° C.)	Heating maintaining period (s)	Cooling rate (° C./s)	Cooling end-point (° C.)	Reheating temperature (° C.)	Reheating maintaining period (s)	Ms point (° C.)	Galvannealing		
101	AA	25	820	60	50	180	400	60	329	Treated	Example	
102		<u>5</u>	820	60	50	160	400	60	309	Treated	Comparative Example	
103		25	820	60	50	<u>260</u>	400	60	329	Treated	Comparative Example	
104	AB	25	780	90	80	200	450	90	354	Untreated	Example	
105		23	<u>680</u>	90	80	140	450	90	261	Untreated	Comparative Example	
106		15	<u>920</u>	90	80	220	450	90	378	Untreated	Comparative Example	
107	AC	73	840	40	30	120	360	40	266	Treated	Example	
108		70	800	<u>5</u>	30	100	360	40	221	Treated	Comparative Example	
109		70	780	30	30	<u>30</u>	360	40	246	Treated	Comparative Example	
110	AD	33	820	20	40	190	500	20	328	Treated	Example	
111		12	780	40	<u>5</u>	170	500	20	294	Treated	Comparative Example	
112		20	800	40	30	<u>300</u>	500	20	343	Treated	Comparative Example	
113	AE	26	740	80	50	220	400	120	352	Treated	Example	
114		<u>2</u>	760	50	50	200	400	120	344	Treated	Comparative Example	
115		20	780	60	50	220	<u>250</u>	30	355	Treated	Comparative Example	
116	20	780	60	50	220	<u>650</u>	60	346	Treated	Comparative Example		
117	20	<u>1000</u>	60	150	200	350	60	390	Treated	Comparative Example		

TABLE 7-continued

Galvanized steel sheet No.	Steel	Annealing conditions							Ms point (° C.)	Galvan- nealing	Note
		Heating rate (° C./s)	Heating temperature (end-point temperature) (° C.)	Heating maintaining period (s)	Cooling rate (° C./s)	Cooling end-point (° C.)	Reheating temperature (° C.)	Reheating maintaining period (s)			
118	AF	30	790	30	25	150	420	60	285	Treated	Example
119		<u>7</u>	810	30	25	100	420	60	285	Treated	Comparative
120		20	800	40	25	160	450	<u>900</u>	285	Treated	Example Comparative
121		25	780	40	25	140	400	<u>0</u>	270	Treated	Example Comparative
122	AG	100	810	40	30	190	470	20	316	Treated	Example
123		<u>5</u>	800	40	30	160	470	20	297	Treated	Comparative Example
124	AH	30	820	60	150	240	380	60	378	Untreated	Example
125		12	830	60	150	<u>320</u>	380	60	367	Untreated	Comparative Example
126	AI	34	820	90	70	250	440	60	409	Treated	Example
127		20	840	90	70	<u>100</u>	440	60	398	Treated	Comparative Example
128	<u>AJ</u>	25	820	60	50	230	420	60	388	Treated	Comparative Example
129	<u>AK</u>	32	840	80	50	150	400	60	291	Treated	Comparative Example
130	<u>AL</u>	30	800	90	50	180	400	60	307	Treated	Comparative Example

TABLE 8

Galvanized steel sheet No.	Microstructure*										Note
	F		Crystal grain		Tensile characteristic values					AE/TS	
	Area	M + residual γ	Tempered M	diameter of second phase (μm)	TS (MPa)	El (%)	TS \times El (MPa \cdot %)	λ (%)	AE (MJ/m ³)		
101	75	5	20	2.2	845	24	20280	80	53	0.063	Example
102	78	4	18	<u>4.5</u>	830	25	20750	75	40	0.048	Comparative Example
103	75	<u>12</u>	13	2.4	870	24	20880	45	54	0.062	Comparative Example
104	71	5	24	2.0	882	22	19404	87	59	0.067	Example
105	85	<u>1</u>	<u>1</u>	1.8	750	20	15000	65	32	0.042	Comparative Example
106	62	7	31	<u>4.2</u>	856	22	18832	72	40	0.047	Comparative Example
107	65	7	28	1.4	1046	20	20920	82	72	0.069	Example
108	71	4	<u>8</u>	1.8	972	17	16524	70	52	0.053	Comparative Example
109	68	<u>1</u>	31	1.5	1010	17	17170	87	73	0.072	Comparative Example
110	70	7	23	2.1	1208	18	21744	74	79	0.065	Example
111	75	<u>2</u>	<u>8</u>	2.4	1070	16	17120	43	54	0.050	Comparative Example
112	67	<u>21</u>	12	2.4	1270	17	21590	24	89	0.070	Comparative Example
113	40	9	51	2.1	1228	16	19648	55	82	0.067	Example
114	44	8	48	<u>5.5</u>	1180	16	18880	58	53	0.045	Comparative Example
115	38	<u>14</u>	48	2.3	1340	14	18760	29	84	0.063	Comparative Example
116	43	<u>2</u>	55	1.9	1023	14	14322	36	62	0.061	Comparative Example
117	<u>4</u>	8	<u>88</u>	<u>7</u>	1280	8	10240	75	65	0.051	Comparative Example

*F ferrite, M martensite, γ austenite

TABLE 9

Galvanized steel sheet No.	Microstructure*				Tensile characteristic values							
	F Area fraction (%)	M + residual γ area fraction (%)	Tempered M Area fraction (%)	Crystal grain diameter of second phase (μm)	TS (MPa)	El (%)	TS \times El (MPa \cdot %)	λ (%)	AE (MJ/m ³)	AE/TS	Note	
118	85	4	11	2.0	742	28	20776	78	51	0.069	Example	
119	85	4	11	<u>3.4</u>	725	29	21025	82	40	0.055	Comparative Example	
120	85	<u>1</u>	14	2.3	693	25	17325	92	45	0.065	Comparative Example	
121	86	<u>12</u>	<u>2</u>	2.1	773	26	20098	43	53	0.069	Comparative Example	
122	72	7	21	1.2	1024	21	21504	65	73	0.071	Example	
123	75	6	19	<u>3.3</u>	995	22	21890	70	53	0.053	Comparative Example	
124	65	8	27	1.7	1286	15	19290	63	91	0.071	Example	
125	69	<u>18</u>	13	2.5	1332	15	19980	23	97	0.073	Comparative Example	
126	60	7	33	2.7	946	23	21758	82	61	0.064	Example	
127	64	<u>1</u>	35	2.5	898	19	17062	95	55	0.061	Comparative Example	
128	90	<u>2</u>	<u>8</u>	1.5	398	38	15124	68	19	0.047	Comparative Example	
129	90	<u>2</u>	<u>8</u>	2.3	309	43	13287	63	13	0.042	Comparative Example	
130	75	6	19	<u>3.4</u>	717	27	19359	70	35	0.049	Comparative Example	

*F ferrite, M martensite, γ austenite

The invention claimed is:

1. A formable galvanized steel sheet, comprising, in terms of % by mass, 0.05 to 0.3% of C, 0.01 to 2.5% of Si, 0.5 to 3.5% of Mn, 0.003 to 0.100% of P, 0.02% or less of S, 0.010 to 1.5% of Al, and 0.01 to 0.2% in total of at least one element selected from Ti, Nb and V, the remainder being Fe and unavoidable impurities, having a microstructure composed of, in terms of area fraction, 20 to 87% of ferrite, 3 to 10% in total of martensite and residual austenite, and 10 to 60% of tempered martensite, a first phase composed of the ferrite, and a second phase composed of the martensite, residual austenite, and tempered martensite having an average crystal grain diameter of 3 μm or less, and having a ratio of absorption energy AE to tensile strength TS (AE/TS) not less than 0.063 as a result of heat applied at a temperature of 500° C. to Ac₁ transformation point at an average temperature rising rate of 10° C./s or more.

2. The formable galvanized steel sheet of claim 1, further comprising at least one composition selected from the group consisting of (A) to (C):

(A): at least one element selected from the group consisting of, in terms of % by mass, 0.005 to 2.00% of Cr, 0.005 to 2.00% of Mo, 0.005 to 100% of Ni, and 0.005 to 2.00% of Cu;

(B): in terms of % by mass, 0.0002 to 0.005% of B; and

(C): at least one element selected from the group consisting of, in terms of % by mass, 0.001 to 0.005% of Ca and 0.001 to 0.005% of REM.

3. The formable galvanized steel sheet of claim 1, wherein the galvanized steel sheet is a galvanized steel sheet.

4. The formable galvanized steel sheet of claim 2, wherein the galvanized steel sheet is a galvanized steel sheet.

5. A method of producing a formable galvanized steel sheet, comprising:

subjecting a slab having an elemental composition of claim 1 to hot rolling and cold rolling thereby making a cold rolled steel sheet;

subjecting the cold rolled steel sheet to annealing including heating the steel sheet in a temperature range from 500° C. to the Ac₁ transformation point at an average temperature rising rate of 10° C./s or more;

heating and maintaining the steel sheet in a temperature range from the Ac₁ transformation point to (Ac₃ transformation point+30° C.) for 10 seconds or more;

cooling the steel sheet to a temperature range from (Ms point-100° C.) to (Ms point-200° C.) at an average cooling rate of 10° C./s or more;

reheating and maintaining the steel sheet in a temperature range from 350 to 600° C. for 1 to 600 seconds; and subjecting the annealed steel sheet to galvanizing treatment.

6. The method of claim 5, wherein the average temperature rising rate from 500° C. to the Ac₁ transformation point is 20° C./s or more.

7. The method of claim 5, wherein the galvanizing treatment is followed by galvannealing treatment.

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